Journal of Engg. Research **Vol. 5 No. (1) March 2017 pp.** *200-219*

دراسة جدوى عن ارتفاع ضغط غمر البخار بعد غمر المياه في خزان النفط الثقيل العادي

***هوي جيان، **تشن وي وي، ***وي باي، ***وانغ جيان تشونغ، ***ليو هاو**

* المختبر الرئيسي الوطني للنفط الثقيل بجامعة الصين للبترول، تشينغداو

** حقل النفط شنغلى لشركة مجموعة دونغ شنغ، دونغ ينغ

***معهد هندسة البترول بجامعة الصين للبترول، تشينغداو

الخلاصة

يكون دفن النفط الثقيل العادي في حقل النفط شنغلى عادة عميقا، ويسبب غمر المياه على المدى الطويل الي ضغط عالي لطبقة الأرض، وزيادة نسبة محتوى الرطوبة، مما يسبب صعوبة التنفيذ الي الغمر بالبخار عالي الضغط بعد غمر المياه. في هذا البحث، يتم دراسة تأثيرات ضغط الخزان ونوعية البخار على حرارة بخار الخزان وتمدد البخار بواسطة نموذج محاكاة لبيان جدوى الغمر بالبخار عالي الضغط. ويتم أخيرا من خلال التطبيق الميداني لمنطقة الاختبار التجريبي في حقول النفط لجزيرة زونج ذونج (Ng5). أظهرت نتيجة الدراسة أنه عندما يكون ضغط الارض ثابت، يكون نوعية البخار كثيفا، وبزيادة انتقال الحرارة يتم توسع البخار بشكل كامل في السطح والعمودي، ويكون تحرك رائدة درجة الحرارة وتشبع الغاز أسرع، ونصف قطر للتسخين كبير. وعندما يكون جفاف البخار ثابت، يكون ضغط طبقة الارض أكبر، وارتفاع درجة الحرارة في غرفة البخار، ويكون تحرك رائدة درجة الحرارة وتشبع الغاز أبطأ، ونصف قطر للتسخين أصغر. وعلى أساس الخصائص العالية للمحتوى الحراري، يمكن حل مشكلة حجم غرفة البخار الصغير بسبب ضغط الخزان العالي ليحقق نفس تأثير التنمية من ضغط الخزان المنخفض وانخفاض نوعية البخار، أي دور «نفس المحتوي ونفس التأثير».

The feasibility study on high pressure steam flooding after water flooding of common heavy oil reservoir

Jian Hou*, Weiwei Ren**, Bei Wei***, Jianzhong Wang*** and Hao Liu***

** State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Qingdao, Shandong 266580, China*

*** Dongsheng Group Co.,LTD of Shengli Oilfield, Dongying, Shandong 257000, China*

**** School of Petroleum Engineering, China University of Petroleum, Qingdao, Shandong 266580, China*

** Corresponding author: houjian@upc.edu.cn (J. Hou), vfengchuiguo@163.com(B. Wei)*

ABSTRACT

The common heavy oil reservoir in Shengli oilfield usually has deeper buried depth andthe reservoir pressure and water cut are both high after long-term water flooding, which makes it difficult to carry out steam flooding after water flooding. In this paper the effects of reservoir pressure and steam quality on steam heating reservoir and steam expansion are studied based on the numerical model; the feasibility of high-pressure steam flooding is also demonstrated. Finally, the development result of high pressure steam flooding is validated through the field practice in Gudao Oilfield Zhong’er’zhong Ng5 pilot test area. The research result shows that when reservoir pressure is constant, the greater the steam quality, the more the carried heat, the more sufficiently the steam expands in vertical and horizontal directions, the faster the temperature front and gas saturation front move, the larger the heating radius. If the steam quality is constant, the greater the reservoir pressure, the higher the steam chamber temperature, the more slowly temperature front and gas saturation front move, the smaller the heating radius. With enhancing the steam quality and taking advantage of its high specific volume and enthalpy, the high pressure steam flooding can resolve the problem of small steam chamber caused by high reservoir pressure so as to achieve the same development effect of low reservoir pressure and low steam quality, namely the function of “equal specific volume and equal effect”.

Keywords: High pressure steam flooding; reservoir heating; steam expansion; the feasibility.

INTRODUCTION

Steam flooding is a method that can improve sweep efficiency of water flooded common heavy oil reservoir and enhance oil displacement efficiency at the same time (Zhao *et al*., 2014; Mozaffari *et al*., 2013; Li et al., 2013a; Li *et al*., 2013b). Since the 1960s, oilfields around the world have successively carried out experimental studies and field tests about conversion of thermal recovery in the late stage of water flooding, and achieved good results (Estremadoyro, 2001; Perez-Perez *et al*., 2001). Since the 1990s, China has carried out the research and field test of EOR technology in several blocks of water flooded reservoir successively (Yang *et al*., 1998; Wu *et al*., 2013; Zhou, 2006). In China, steam flooded heavy oil reservoir after water flooding has the characteristics of the deep burial and high oil viscosity. There have been many studies of the mechanisms of steam flooding in water flooded heavy oil reservoir through the “dual-model” experiments (Gu, 2014; Bagheripour *et al*., 2012; Hoffman & Kovscek 2004). As early as 1961, Willman studied the contribution of each mechanism in steam flooding process. Steam distillation, gas drive and solvent extraction can greatly improve the effect of steam flooding. Chu (1988 studied the mechanisms of steam flooding in water flooded reservoir through numerical reservoir simulation. For 30°API oil, the main mechanisms include steam distillation, viscosity reducing and the influence of temperature on the relative permeability. In 2008 Wu et al. studied the effect of steam distillation on the development result of light oil reservoir by dividing into three pseudo-components and established the relation between viscosity and distillation rate. When oil viscosity is less than 50mPa·s, steam distillation cannot be neglected. In 2009 Guan et al. carried out physical model experiments of steam flooding after water flooding by using three-dimensional high pressure scale model. The result shows that the main mechanism is to improve the vertical development degree through steam overlap and achieve the even sweep, thus control the rise of water cut in late water flooding stage. Pang et al. (2013) established the two-dimensional and three-dimensional physical model of real water drive sandstone reservoir based on similar criteria and studied microcosmic oil incremental mechanism of steam flooding after water flooding. The results show that steam distillation and steam drive are the main mechanisms for steam flooding. For the researches above, the mechanism in water flooded heavy oil reservoir differs from that in common heavy oil reservoir. Water flooded heavy oil reservoirs are generally low oil viscosity common heavy oil and light oil reservoirs. There are lots of light fractions in crude oil. The main mechanism of steam flooding is steam distillation, that is, in the steam injection process, vaporization pressure is reduced because of the presence of steam, which makes light hydrocarbon can be easily distilled from crude oil, so that the residual saturation after water flooding is greatly reduced. What is following is the oil viscosity reduction effect. What is more, for the positive rhythm reservoir, the steam overlap can be used to displace the upper unswept oil reservoir in water flooding and to increase sweep efficiency and enhance oil recovery.

Operating conditions have significant impacts on the development of steam flooding. To achieve successful steam flooding, the reservoir pressure (*P, MPa*) and bottom-hole steam quality (x, dimensionless unit) are the crucial factors (Zhang *et al*., 2008). As for the steam flooding, the lower the reservoir pressure is, the better the result is, and generally the reservoir pressure is lower than 5MPa, and better between 1MPa and 3MPa, because the specific volume is large in this pressure range and steam chamber volume can also be larger. When reservoir pressure is higher than 5MPa, steam flooding belongs to the category of high pressure steam flooding. In addition, the bottom-hole steam quality level not only determines the heat amount carried by steam and the effects of reservoir heating, but also determines whether the steam chamber can form and expand steadily, directly determining the effectiveness of steam flooding development. However, the common heavy oil reservoir in Shengli oilfield is deeply buried, and the long-term water flooding results in high reservoir pressure and water cut (fw, dimensionless unit), and when steam flooding is adopted, it leads to low bottom-hole steam quality with small steam chamber and low heat energy utilization rate, which becomes the technological bottleneck of steam flooding after water flooding. Therefore, it is of great importance to study the effects of reservoir pressure and steam quality on steam flooding.

In this paper the numerical simulation model of Gudao Oilfield Zhong'er'zhong Ng5 pilot area is established, with which the effects of reservoir pressure and steam quality on reservoir heating and steam expansion is studied. Based on the effects above and reservoir characteristics of the pilot area, we discuss the feasibility of high pressure steam flooding, and finally the development result of high pressure steam flooding is validated through the field test in Gudao Oilfield Zhong'er'zhong Ng5 pilot test area.

ESTABLISHMENT OF NUMERICAL SIMULATION MODEL

The study object of steam flooding after water flooding is four 200×283m inverted nine-spot well groups in central water injection area of Gudao oilfield Zhongerzhong Ng5 pilot area. We establish the numerical simulation model of the study object, as shown in Figure 1. The model consists of six small simulation layers. The grid is divided into 41×41×6 with an oil area of $0.64km^2$, a geological reserves of 171.44×10^4t whose buried depth is 1275m with an effective thickness of 13.5m, a porosity of 0.32, a permeability of $1460\times10^{-3}\mu m^2$, an initial oil saturation of 0.65, an original reservoir pressure of 12.2MPa, and an original reservoir temperature of 65℃. Viscosity-temperature curve is shown in Figure 2. Oil-water relative permeability curve is shown in Figure 3.

Since Gudao oilfield Zhongerzhong Ng5 pilot test area was put into production in August 1982, it has been 33 years. It can be divided into five stages. (1) Elastic recovery with low and medium water cut (August 1982~August 1985); (2) Water injection development with the water cut decreasing first and increasing later (September 1985~October 1991); (3) Forced injection and production of low speed with extremely high water cut (January 1992~April 2003); (4) High water cut wells shut in, water injection wells stop and polymer injection starts(May 2003~May 2004); (5) Water injection and thermal recovery (May 2004~ present).

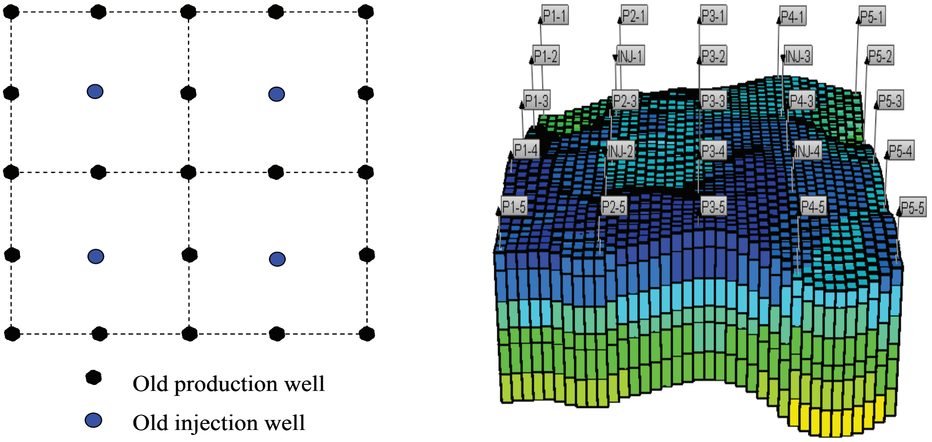

Fig. 1(a) Water flooding well pattern **Fig.** 1(b) Numerical simulation model of pilot test area

Fig. 1 Numerical simulation model of water flooded common heavy oil reservoir

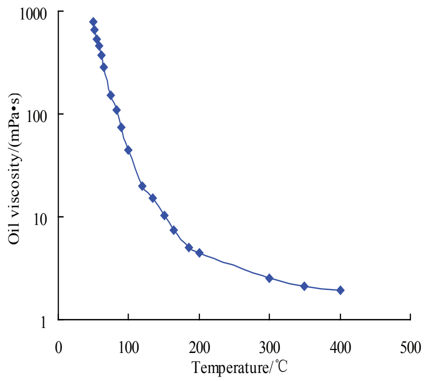

Fig. 2. Viscosity-temperature curve

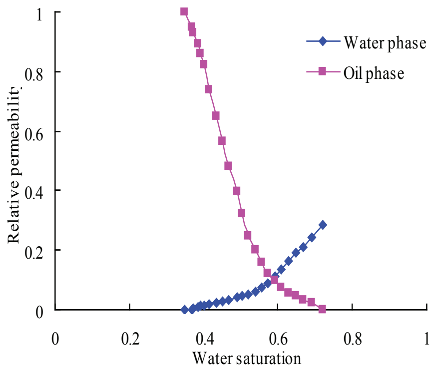

Fig. 3. Oil-water relative permeability curve

We fit the water flooding process of Gudao Oilfield Zhong'er'zhong Ng5 pilot test area from June 1st in 1982 to May 1st in 2004. The water cut fitting curve is shown in Figure 4. The recovery factor of water flooding is 19.17%.

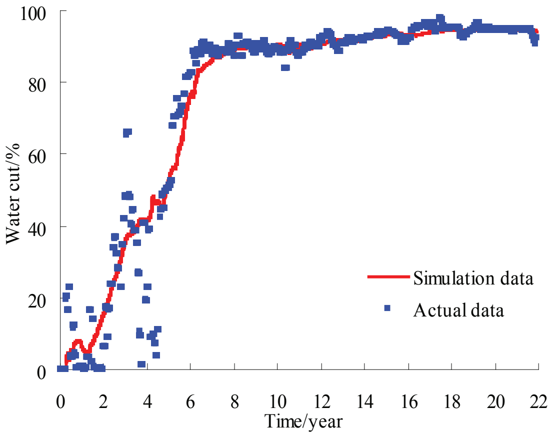

Fig. 4. Water cut fitting curve

How to choose the thermal recovery well pattern is the key to the success of steam flooding. It is the configuration relationship of thermal recovery well pattern and the original water injection channel that has great impact on the development result of steam flooding. Through controlling the new well steam injection and old well fluid amount, the driving system and direction are changed to overcome the influence of the original water flooding system and realize the most efficient use of heat. The original water flooding injection-production well spacing is 200×283m in Zhong'er'zhong Ng5 pilot test area. According to the seepage law of common heavy oil thermal recovery, the maximum effective heating radius for steam stimulation is between 60m and 70m. To guarantee the basic thermal communication between wells for steam flooding after steam stimulation, the original injector-producer well spacing is too large and should be controlled within 150m. Additionally old wells are conventionally completed and cannot satisfy thermal recovery requirements. Therefore, a batch of thermal recovery wells needs to be deployed in the pilot test area. On the basis of the study of residual oil saturation distribution, the well pattern form is optimized. It is encrypted in the sub-mainstream line direction of water flooding. Encrypted well streamline transfers 90°, and edge well streamline transfers 45°, as shown in Figure 5.

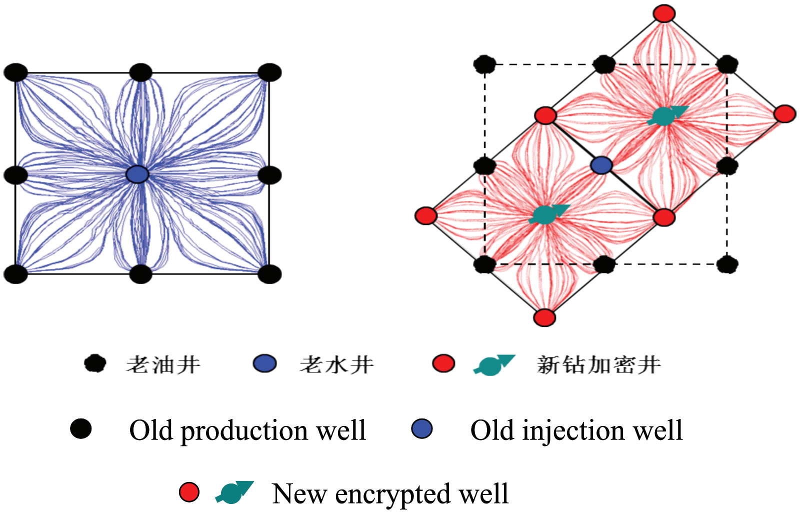

Fig. 5(a) Inverted nine-spot water flooding well pattern

Fig. 5(b) Inverted nine-spot thermal recovery well pattern

Fig. 5 Well pattern adjustment sketch map of thermal recovery after water flooding

After the thermal recovery well pattern is adjusted, we use steam stimulation to reduce the pressure. The original injection wells are shut in, while the original production wells and encrypted new wells are used for steam stimulation. The steam injection parameters include steam injection intensity of 100t/m, steam injection rate (is,t/h) of 4.2t/h, steam injection time of 13 days, soak time of 4 days, liquid rate of 50m3/d for single well and three cycles. The reservoir pressure decreases to about 7MPa after stimulation. The recovery factor of steam stimulation stage is 10.7%. The recovery factor of water flooding and steam stimulation stage reaches 29.87%.

To conveniently analyze the effects of pressure, steam quality and other parameters on steam flooding, a typical inverted nine-spot steam drive well group is cut out, as shown in Figure 6. Optimization of injection and production parameters of steam flooding is carried out through the numerical simulation method. The production-injection ratio is set to 1.2. The steam injection intensity is set to be 1.6 m3/(d·ha·m) and the steam quality 0.6.

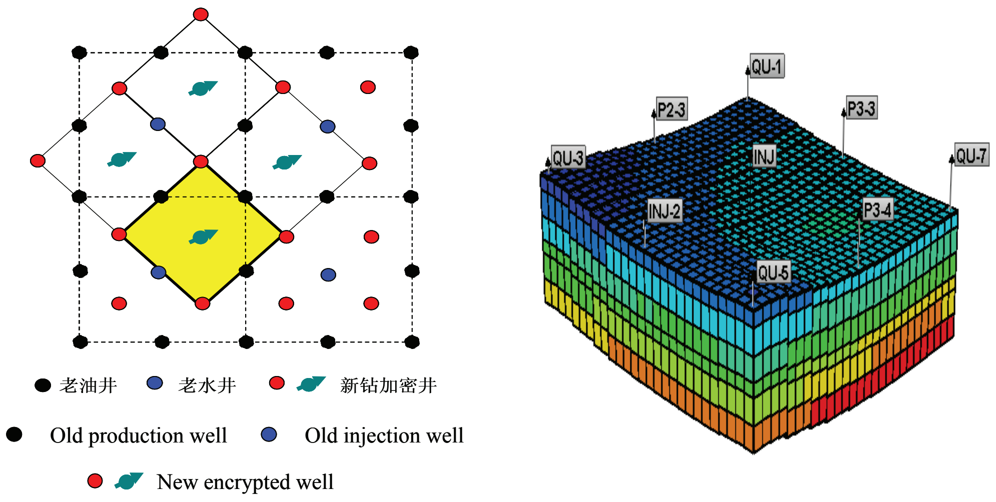

Fig. 6(a) Well pattern for steam flooding stage

Fig. 6(b) Numerical simulation model of typical well groups for steam flooding stage

Fig. 6. Numerical simulation model of steam flooding in water flooded heavy oil reservoir

EFFECT OF RESERVOIR PRESSURE AND STEAM QUALITY ON RESERVIOR HEATING

To analyze the mechanism of reservoir pressure and steam quality on reservoir heating, the fourth vertical layer between well INJ and QU-7 of the typical inverted nine-spot steam drive well group model is selected as the research object. During the steam spreads from the injection well to the production well, a number of different temperature and fluid saturation zones are formed (Romanov & Hamouda, 2011; Wang *et al*., 2012), as shown in Figure 7, in which A represents steam zone, B represents the hot water condensation zone, C means the oil and cold water zone, D means the original reservoir zone and E is the steam stimulation heating zone.

The displacement mechanism is different in different zones. Oil saturation distribution mainly depends on the thermal characteristics of crude oil itself. Oil saturation in the steam zone decreases to the minimum. It has nothing to do with the value of the original oil saturation, but depends on the steam temperature and composition of crude oil. Gas saturation in the zone is constant, and the heat convection plays a leading role. In the hot water condensation zone, the steam condenses into water, and gas saturation drops to zero, while water saturation increases to the maximum. The oil and cold water zone forms in front of the hot water condensation zone. With the increase of the distance from steam injection well, the oil saturation rises and the water saturation declines in the region. In the area where heat hasn’t influenced, reservoir temperature and oil saturation are still in a state of nature, which is named as the original reservoir zone. Near the production well, because of several cycles of steam stimulation before high pressure steam flooding, the oil saturation is lower than the original oil saturation and the water saturation on the rise, forming the stimulation heating zone.

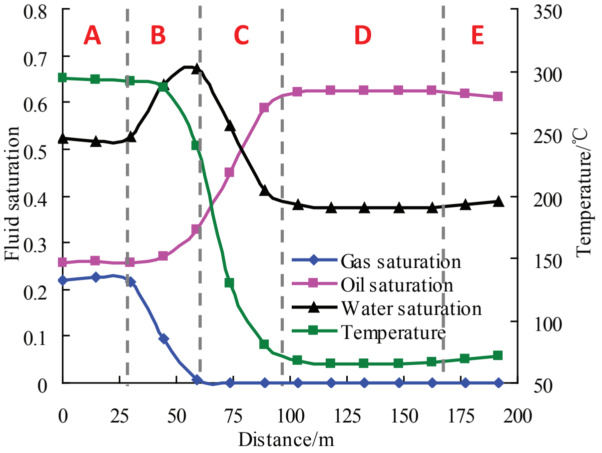

Fig. 7. Production performance along with the change of distance (injection for 2 years)

According to the characteristics of the divided zone, temperature distribution curve has been used to study the effect of formation pressure and steam quality on reservoir heating. Temperature distribution curves of six small layers section, which have been injected for 2 years are taken arithmetic average, and then the average temperature distribution curve is obtained, as shown in Figure 8. The average temperature of the hot zone is T_h, and the original reservoir (the cold area) temperature is T_i. We define the distance from injection well corresponding to the temperature $\left(T_h + T_i\right)$ as the heating radius of steam flooding at the moment. Using this method the heating radius (r, m) of basic model, which have been injected for 2 years is 67.4 m.

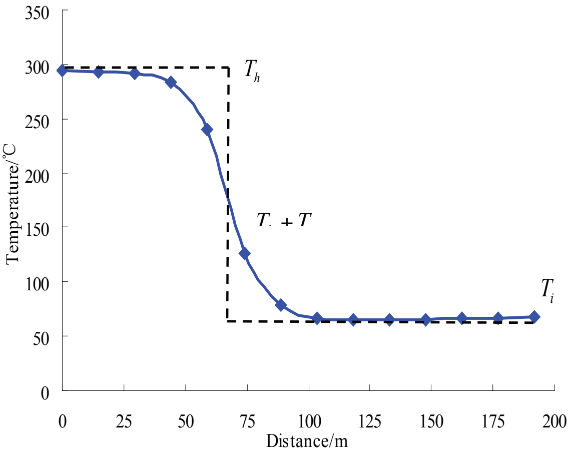

Fig. 8. Heating radius by numerical simulation method

Effect of reservoir pressure

To study the effect of reservoir pressure on reservoir heating, we take the horizontal and vertical temperature field distribution and reservoir heating radius as the research object, and steam quality is 0.6 and formation pressure ranges from 2 to 7MPa, as shown in Figures 9 and 10. The figure shows that when the steam quality is constant, the higher formation pressure is, the higher the steam chamber temperature is, but the more slowly the temperature front moves and the smaller the heating radius is. Besides, the expansion of the longitudinal temperature field area also decreases with the increasing of formation pressure. This is because water saturated temperature and saturated pressure are corresponding under the saturation state. The greater the formation pressure is, the bigger the high temperature area is. But the steam specific volume decreases with the increase of pressure, therefore the formed steam chamber volume and heating radius are both smaller.

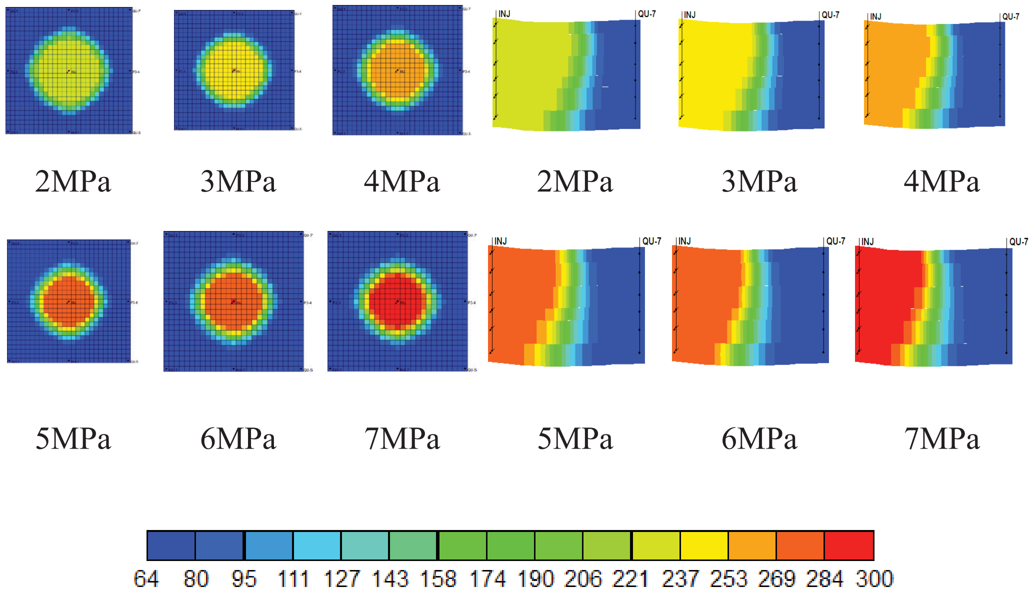

Fig. 9(a) Horizontal temperature field distribution

Fig. 9(b) Vertical temperature field distribution

Fig. 9. Effect of formation pressure on temperature field distribution when injection for 2 years, the color bar represents the temperature.

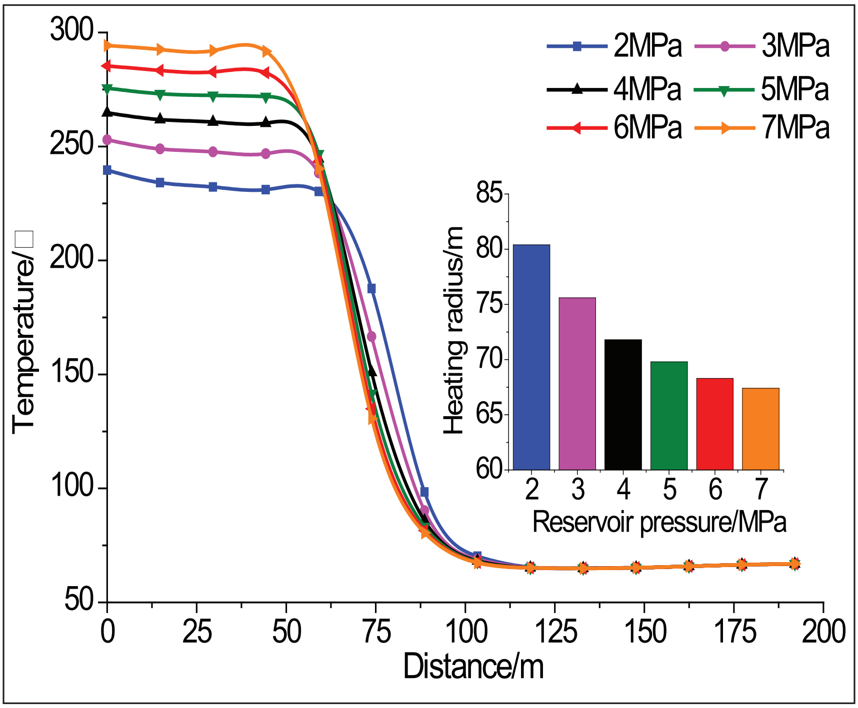

Fig. 10. Effect of formation pressure on temperature distribution and heating radius

Effect of steam quality

To study the effect of steam quality on reservoir heating, we take the horizontal and vertical temperature field distribution and reservoir heating radius as the research object, and the formation pressure is 7MPa and steam quality ranges from 0.3 to 0.8, as shown in Figures 11 and 12. The figure shows that when the reservoir pressure is constant, the greater the steam quality, the larger the carried heat, the more fully the steam expands in vertical and horizontal directions, and the larger the high temperature area. With the increase of the steam quality, the horizontal section of temperature distribution curve remains the same, which is because the main determining factor is the reservoir pressure rather than the steam quality. But if the steam quality is higher, the heat enthalpy of saturated steam and heating radius is larger.

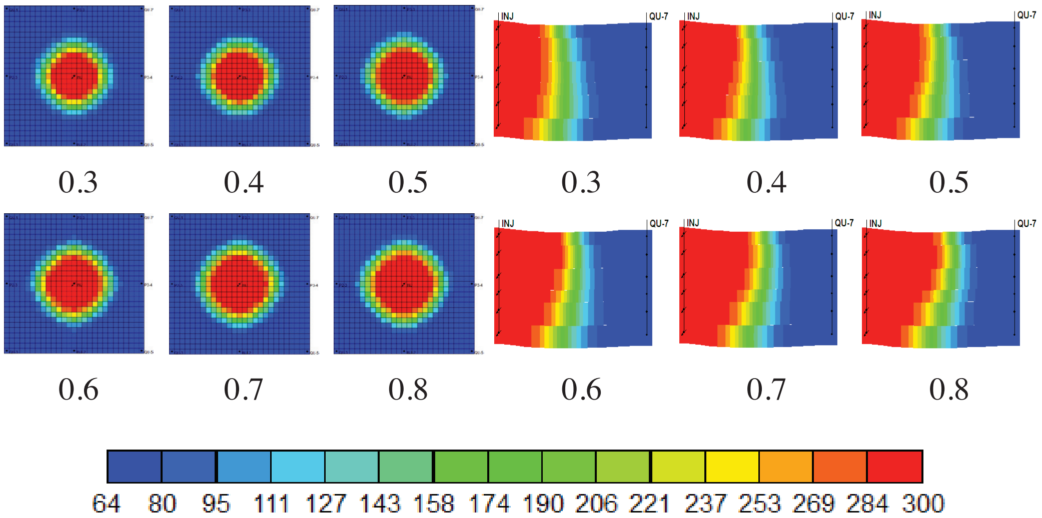

Fig. 11(a) Horizontal temperature field distribution

Fig. 11(b) Vertical temperature field distribution

Fig. 11. Effect of steam quality on temperature field distribution when injection for 2 years, the color bar represents the temperature.

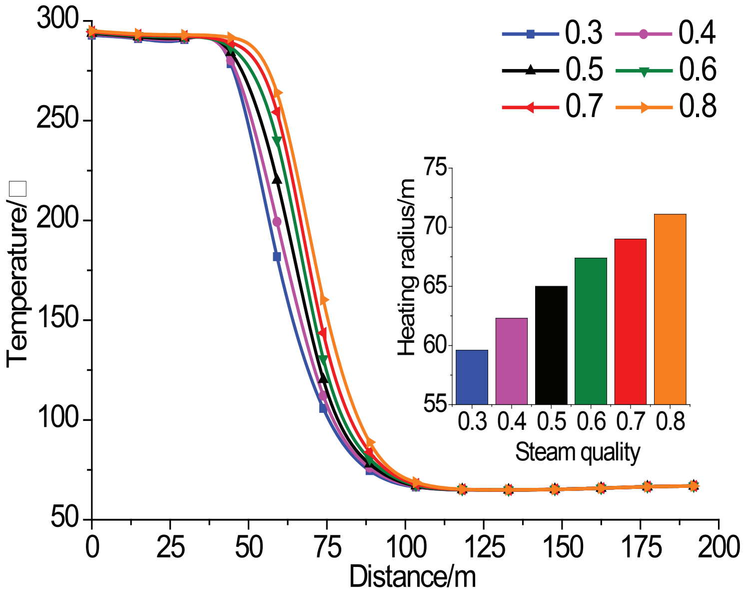

Fig. 12. Effect of steam quality on temperature distribution and heating radius

The influence of reservoir pressure and steam quality on heating radius is shown in Figure 13. When the steam quality is constant, the reservoir pressure increases from 2MPa to 7MPa (increasing by 2.5 times), subsequently the heating radius decreases by about 15%. When reservoir pressure is constant, the steam quality increases from 0.3 to 0.8 (increasing by1.67 times), subsequently the heating radius increases by about 20%. This suggests that the influence of the steam quality on heating radius is greater than that of reservoir pressure.

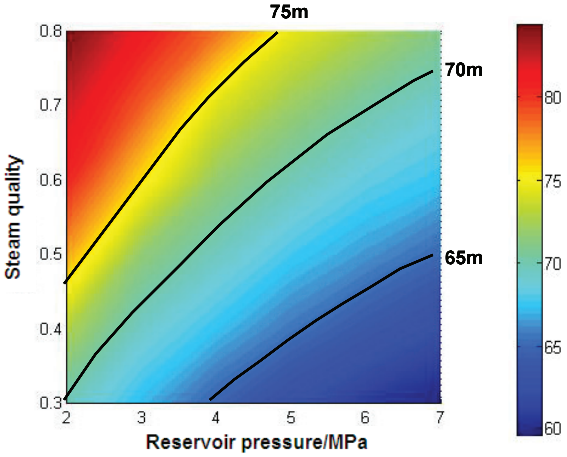

Fig. 13, Effect of formation pressure and steam quality on heating radius

EFFECT OF RESERVOIR PRESSURE AND STEAM QUALITY ON STEAM EXPANSION

The temperature of the reservoir near wellbore begins to rise due to steam heating after the steam is injected. Then steam chamber zone begins to spread and form in the horizontal direction. Steam zone expands quickly to the edge well of close distance, and slowly to the corner well of remote distance, at which the expansion of the steam zone is balanced. After the steam zone breaks through the edge well, the expansion of steam zone to the corner well direction becomes so slow that it may stop, which results in a small steam zone volume, at which the expansion of the steam zone is unbalanced. This paper mainly studies the influence of reservoir pressure and steam quality on steam expansion.

In this paper, steam chamber expansion fraction is defined as the ratio of the steam chamber volume and the total pore volume. It represents the degree of steam chamber expansion. The steam chamber expansion fraction (Ra) is defined as follows:

$$R_a = {}^{V}\!/_{V_f} \times 100\% \qquad (1)$$

Where Ra is steam chamber expansion fraction, V is the volume of steam chamber and V_f is the total pore volume.

Effect of reservoir pressure

To study the effect of reservoir pressure on steam expansion, we take the horizontal and vertical gas saturation field distribution, gas saturation front movement and steam chamber expansion fraction as the research object, and the steam quality is 0.6 and reservoir pressure ranges from 2 to 7MPa, as shown in Figures 14 and 15. The figure shows that when steam quality is constant, with the increase of reservoir pressure, the expansion of steam in the horizontal and vertical section is more inadequate. Besides, gas saturation front moves more slowly and steam chamber expansion fraction is smaller. This is because when steam quality is constant, the steam specific volume decreases with the increase of pressure, and effect of the pressure on steam specific volume is bigger when the steam quality is lager.

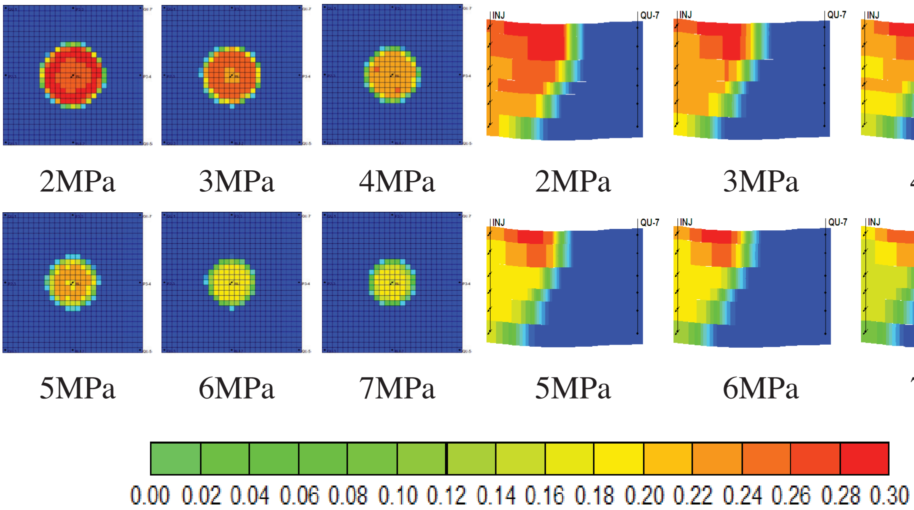

Fig. 14(a) Horizontal gas saturation field distribution

Fig. 14(b) Vertical gas saturation field distribution

Fig. 14. Effect of formation pressure on gas saturation field distribution when injection for 2 years, the color bar represent the gas saturation

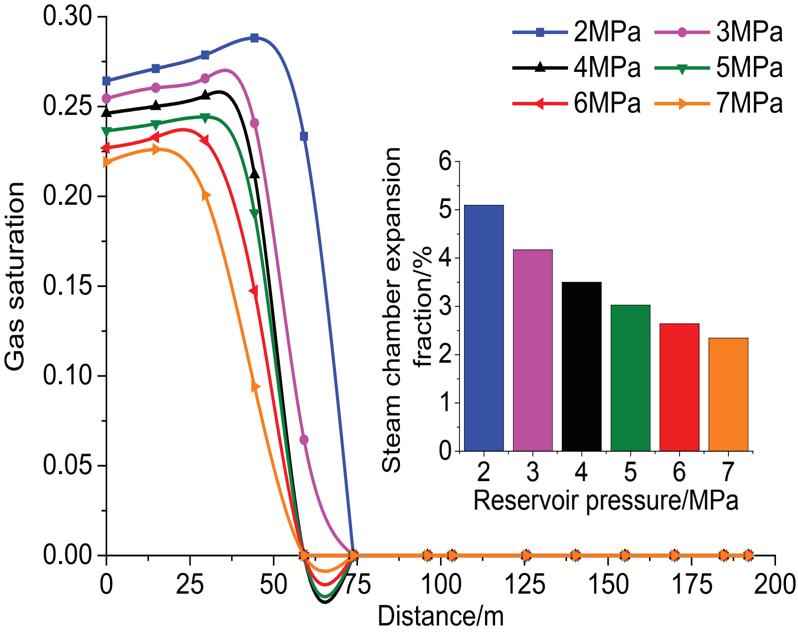

Fig. 15. Effect of formation pressure on gas saturation distribution and steam chamber expansion fraction

Effect of steam quality

To study the effect of steam quality on steam expansion, we take the horizontal and vertical gas saturation field distribution, gas saturation front movement and steam chamber expansion fraction as the research object, the reservoir pressure is 7MPa and steam quality ranges from 0.3 to 0.8, as shown in Figures 16 and 17. The figure shows that when reservoir pressure is constant, with the increase of steam quality, the amount of heat is larger and the expansion of steam in the horizontal and vertical section is more adequate. The gas saturation front moves faster and steam chamber expansion fraction is bigger with the increase of steam quality.

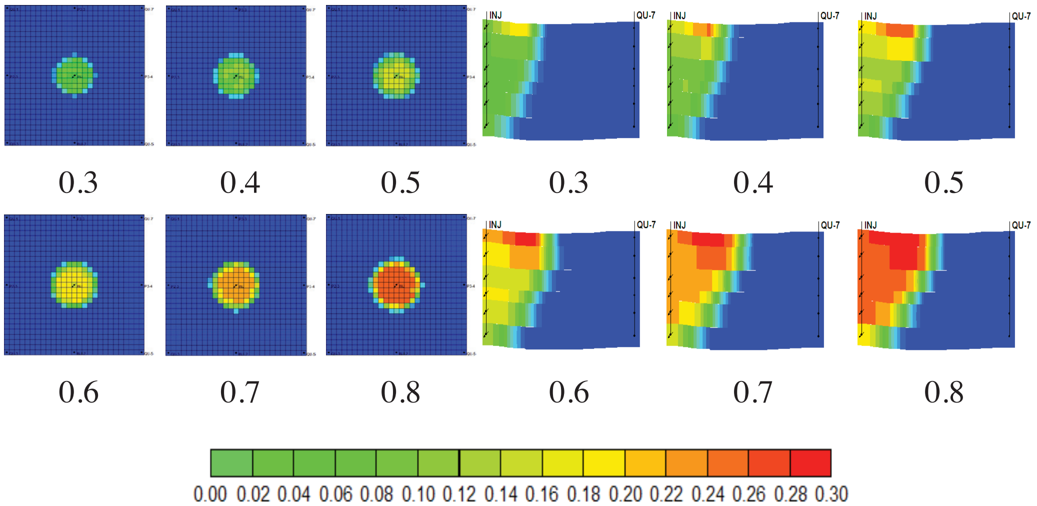

Fig. 16(a) Horizontal gas saturation field distribution

Fig. 16(b) Vertical gas saturation field distribution

Fig. 16. Effect of steam quality on gas saturation field distribution when injection for 2 years, the color bar represent the gas saturation.

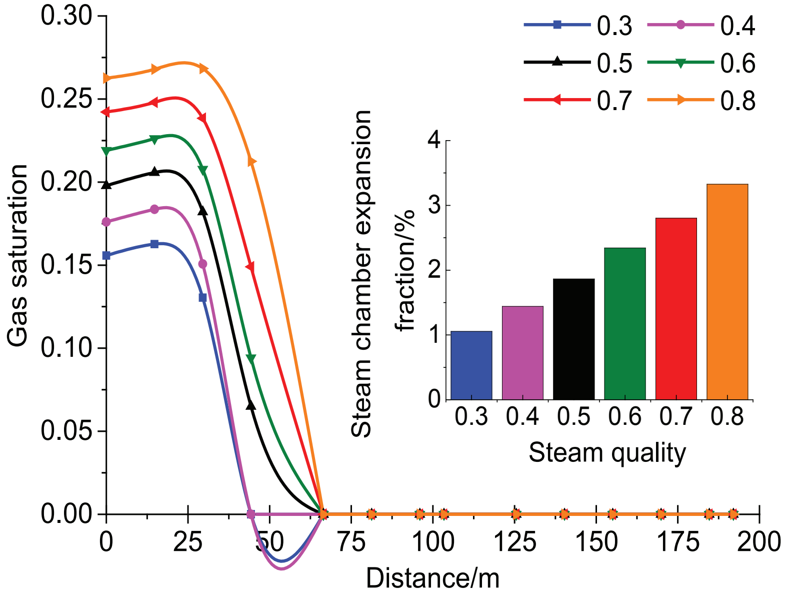

Fig. 17. Effect of steam quality on gas saturation distribution and steam chamber expansion fraction

The influence of reservoir pressure and steam quality on steam chamber expansion fraction is shown in Figure 18. When reservoir pressure increases from 2MPa to 7MPa (increasing by 2.5 times) under a steam quality of 0.3, the steam chamber expansion fraction decreases by about 67%. But with the increase of the steam quality the percentage of steam chamber expansion fraction decreases under the same reservoir pressure range. When the steam quality increases from 0.3 to 0.8 (increasing by 1.67 times) under a reservoir pressure of 2MPa, the steam chamber expansion fraction doubles. While with the increase of reservoir pressure, the increased times of steam chamber expansion fraction increases under the same steam quality range. This suggests that the effect of steam quality on steam chamber expansion fraction is greater than that of reservoir pressure.

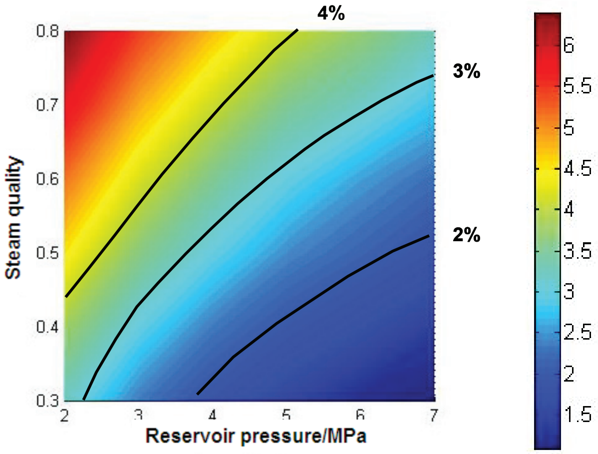

Fig. 18. Effect of formation pressure and steam quality on steam chamber expansion fraction

FEASIBILITY ANALYSIS OF HIGH PRESSURE STEAM FLOODING IN WATER FLOODED HEAVY OIL RESERVOIR AND FIELD PRACTICE

On the basis of the effects of reservoir pressure and steam quality on reservoir heating and steam expansion, the feasibility of steam flooding after water flooding is analyzed in view of the reservoir characteristics of Gudao oilfield Zhongerzhong Ng5 pilot test area.

From the curve of steam specific volume based on different pressure and different steam quality as shown in Figure 19(a), we know that the greater steam quality is, the larger steam specific volume is under the same pressure. The specific volume of 7MPa and steam quality 0.6 is 0.0171m3/kg, and specific volume of 5MPa and steam quality 0.4 is 0.0166m3/kg. It is increased by 3.01%, which shows that the specific volume of high pressure and steam quality can reach the same effect with low pressure and steam quality. The effect of reservoir pressure and steam quality on recovery factor is shown in Figure 19(b) through reservoir numerical simulation method.

The results show that the lager steam quality is, the greater the steam flooding recovery factor is under the same reservoir pressure. But with the increase of reservoir pressure, the recovery factor of steam flooding reduces under the same steam quality. And the effect of pressure on the development result in low pressure area (2~5MPa) is greater than that in high pressure (6~10MPa). The recovery factor of 7MPa and steam quality of 0.6 is approximately equal to that of 5MPa and steam quality 0.5. This is because the steam specific volume and enthalpy are both high under high pressure, and can overcome the influence of pressure and achieve the same development effect of low pressure and steam quality. That is the “equal specific volume and equal effect “. Therefore, the steam flooding is feasible at the reservoir pressure of 7MPa by raising the bottom-hole steam quality.

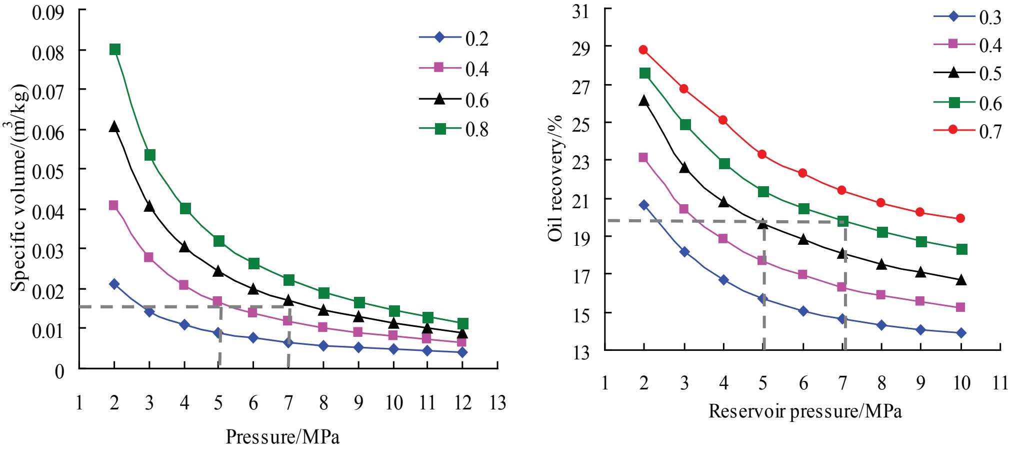

Fig. 19(a) Steam specific volume curve **Fig. 19(b)** Oil recovery factor curve

Fig. 19. Effect of pressure and steam quality on steam specific volume and oil recovery factor

In steam flooding model the instantaneous oil-steam ratio is 0.1 as the ending condition. The recovery factor of steam flooding stage is 20.07%, and the total recovery factor of the whole development stage is 49.94%. The recovery factor along with the change of production time curve is shown in Figure 20.

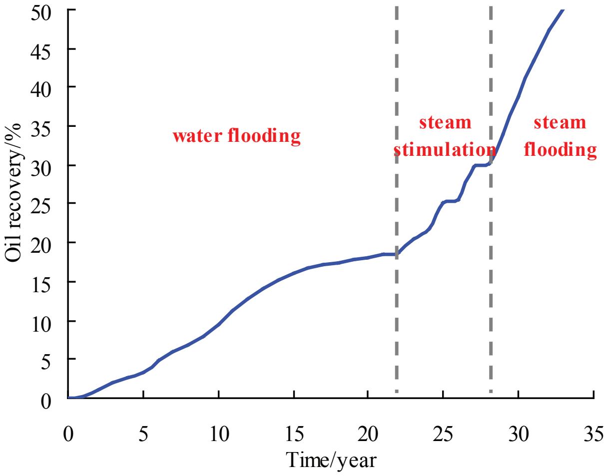

Fig. 20. The recovery degree along with the change of time curve (7MPa)

In Gudao Zhong'er'zhong Ng5 block, four water flooding well groups have been encrypted successively in diversion line direction since 2007, forming four 141x200m inverted nine pilot test well groups with 14 new wells and 11 old wells. To reduce reservoir pressure, set up heat communication between wells and achieve the condition of steam flooding, the steam stimulation has first been carried out in new wells, which is the inevitable stage of steam flooding. Before steam stimulation, for pilot test well group the oil rate is 15t/d, water cut, 88.8%, water flooding recovery factor, 18.8%, and predicted recovery factor of water flooding, 24.1%. New wells adopt thermal recovery by steam injection during steam stimulation. The daily oil rate at peak reaches 103t/d, increasing by 88 t/d more than that of water flooding stage. The average water cut is 81.7%, reducing by 7.1% more than that of water flooding stage. The cumulative increased oil is 110,000 tons during steam stimulation stage, improving the recovery factor of 9.6%.

Through steam stimulation, the reservoir pressure drops to about 7MPa, test well groups were changed to steam flooding on 15th September, 2011, as is shown in Figure 21. After steam flooding, the liquid rate of test well groups increases from 243.9t to 488.5t. The oil rate increases from 43.29t to 102.9t. The water cut decreases from 82.7% to 81.9%. By September 2014, the cumulative oil of steam flooding is 78,400 tons, increasing by 39,400 tons. The cumulative oil-steam ratio is 0.17. The increased oil recovery is 3.4%. Currently the cumulative oil of stimulation and steam flooding is 155,000 tons, and the oil recovery increases by about 13.0%. The predicted rate of oil recovery can reach about 48.9%, increasing by 24.8% more than that of water flooding. The oil recovery of water flooded common heavy oil reservoir is enhanced significantly.

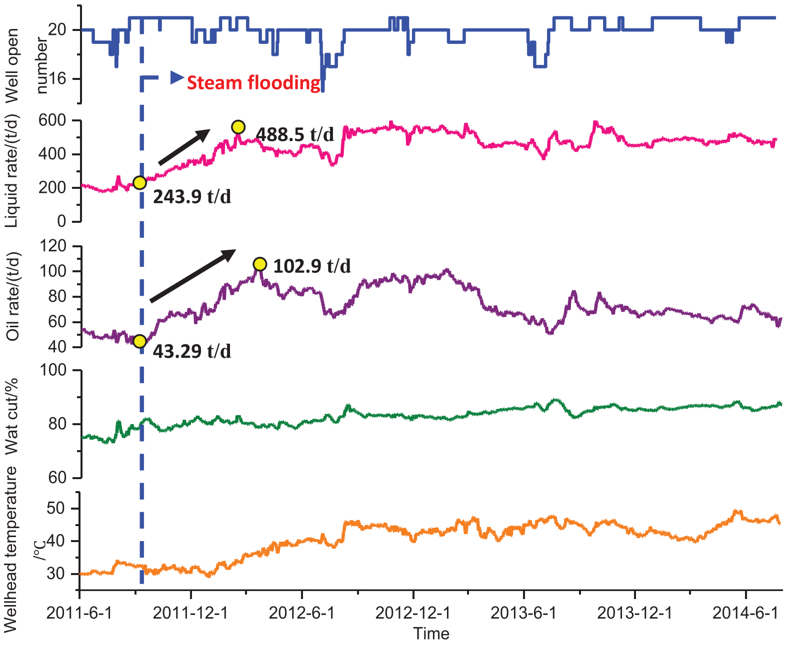

Fig. 21. The development curve of test well groups in Gudao Zhong'er'zhong Ng5 steam flooding pilot test area

CONCLUSIONS

The effects of reservoir pressure and steam quality on reservoir heating is studied through reservoir numerical simulation method. Several different temperature and fluid saturation zones are formed between injection and production wells, and include steam zone, hot water condensation zone, oil and cold water zone, original reservoir zone and stimulation heating zone. If the steam quality is constant, the greater the reservoir pressure, the higher the steam chamber temperature, but the slower the temperature front moving, the smaller heating radius. When the reservoir pressure is constant, the greater the steam quality is, the more sufficiently the steam expands in vertical and horizontal directions, the bigger the heating radius, while the horizontal section of temperature distribution curve remains the same.

The effects of reservoir pressure and steam quality on steam expansion are studied through reservoir numerical simulation method. When the steam quality is constant, with the increase of reservoir pressure, the expansion of steam in the horizontal and vertical directions becomes more inadequate. Besides, the gas saturation front moves more slowly and the steam chamber expansion fraction is smaller. If the reservoir pressure is constant, with the increase of steam quality, the expansion of steam in the horizontal and vertical directions becomes more adequate. The gas saturation front moves faster and steam chamber expansion fraction is bigger with the increase of steam quality.

The oil development schemes with different steam specific volume, pressure and steam quality suggest that the recovery percentages when pressure is 7MPa and quality is 0.6 is approximately equal to the recovery percentages when pressure is 5MPa and quality is 0.5. That is the function of “equal specific volume and equal effect”. Therefore, steam flooding is feasible at the reservoir pressure of 7MPa by raising the bottom-hole steam quality. Finally the development result of high pressure steam flooding is validated through the field practice in Gudao Oilfield Zhong’er’zhong Ng5 pilot test area, providing the basis for the high pressure steam flooding in the field.

ACKNOWLEDGEMENTS

The authors greatly appreciate the financial support of the Important National Science and Technology Specific Projects of China (Grant no. 2016ZX05011-003), the Fundamental Research Funds for the Central Universities (Grant no. 15CX08004A, 13CX05007A, 15CX06025A, 14CX05025A) and the Program for Changjiang Scholars and Innovative Research Team in University (Grant no. IRT1294).

REFERENCES

Bagheripour Haghighi, M., Ayatollahi, S. & Shabaninejad, M. 2012. Comparing the performance and recovery mechanisms for steam flooding in heavy and light oil reservoirs. Calgary, Alberta, Canada. SPE 144797.

Chu, C. 1988. A comprehensive simulation study of steam flooding light-oil reservoirs after waterflood. Journal of petroleum technology, **40**(7):894-904.

Estremadoyro, J.G. 2001. The use of a simulation model to optimize reservoir management in a very mature 24Z reservoir. Elk Hills, California. SPE 68843.

Gu, Q.J. 2014. Simulation study of steam-flooding mechanisms and influence factors in light-oil reservoirs after water-flooding. Applied Mechanics and Materials, **508**:165-168.

Guan, W.L., Wu, S.J. & Liang, J.Z. 2009. 3D physical model of steam injection in high water-cut reservoir. Acta Petrolei Sinica, **3**:017.

Hoffman, B.T. & Kovscek, A.R. 2004. Efficiency and oil recovery mechanisms of steam injection into low permeability, hydraulically fractured reservoirs. Petroleum Science and Technology, **22**(5-6):537-564.

Li, W.G., Yang, S.L., Yang, X.Y., Xu, R.R. & Wang, Z.L. 2013a. A study on the heat penetrating coupling unsteady state model of heavy oil during steam flooding. Petroleum Science and Technology, **31**(17):1697-1706.

Li, W.G., Yang, S.L., Li, M., Wang, H.Y. & Chen, M. 2013b. The heat-flux-solid coupling model of heavy oil during steam flooding. Petroleum Science and Technology, **31**(24):2596-2603.

Mozaffari, S., Nikookar, M., Ehsani, M,R., Sahranavard, L., Roayaie, E. & Mohammadi, A.H. 2013. Numerical modeling of steam injection in heavy oil reservoirs. Fuel, **112**:185-192.

Pang, J., Liu, H. & Li, H.L. 2013. Experiment on EOR mechanism of steam flooding after water flooding. Petroleum Geology & Recovery Efficiency, **2013**:4:018.

Perez-Perez, A., Gamboa, M., Ovalles, C. & Manrique, E. 2001. Benchmarking of steamflood field projects in light/medium crude oils. Kuala Lumpur, Malaysia, SPE 72137.

Romanov, A. & Hamouda, A. A. 2011. Heavy oil recovery by steam injection, mapping of temperature distribution in light of heat transfer mechanisms. Jakarta, Indonesia. SPE 145733.

Wang, J.Y., Ezeuko, C.C. & Gates, I.D. 2012. Energy (Heat) distribution and transformation in the SAGP process. Calgary, Alberta, Canada. SPE 157808.

Willman, B.T., Valleroy, V.V., Runberg, G.W., Cornelius, A.J. & Powers, L.W. 1961. Laboratory studies of oil recovery by steam injection. Journal of Petroleum Technology, **13**(07):681-690.

Wu, S.H., Qian, Y., Shen D.H., Zhang, Z. Y., Zhao, X., Li, Q.Y. & Liu, H.L. 2013. A case study: Steam flooding to enhance recovery of a waterflooded light-oil reservoir. Jakarta, Indonesia. SPE 166666.

Wu, S., Guan, W.L., Ma, D.S., Shen, D.H., Liang, J.Z. & Wang, X.J. 2008. Utilizing steam injection to improve the performance of mature waterflooding reservoir. Perth, Australia. SPE 116549.

Yang, R.Q., Y., Yang, S.Z., Zou, Z.Y. & Zhao, F.Z. 1998. Tests of conversion into steam stimulation following water flooding in Karamay conglomerate oilfield. Beijing, China. SPE 50894.

Zhang, Y.T., Li, X.H., L. & Zhang, X. 2008. Four fundamental principles for design and follow-up of steam flooding in heavy oil reservoirs. Petroleum Exploration & Development, **35**(6):715-719.

Zhao, D.W., Wang, J. & Gates, I.D. 2014. Thermal recovery strategies for thin heavy oil reservoirs. Fuel, **117**:431-441.

Zhou, Y.J. 2006. Studies and practices on the steam injection EOR of water drived heavy oil reservoirs in Shengli petroliferous province. Petroleum Exploration & Development, **33**(4):479.